Chapter

NAVIGATION OPERATIONS WITH PROTOTYPE COMPONENTS OF AN AUTOMATED REAL-TIME SPACECRAFT NAVIGATION SYSTEM

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Abstract: At present, ground navigation support for interplanetary spacecraft requires human intervention for data pre-processing, filtering, and post-processing activities; these actions must be repeated each time a new batch of data is collected by the ground data system. ARTSN, the Automated Real-Time Spacecraft Navigation system, is a prototype of a software system for navigation systems that are in the planning stage. It has established new paradigms for deep space navigation operations by introducing new capabilities to the navigation analyst: (1) automated radio metric data validation and correction, (2) real-time monitoring of spacecraft and tracking station performance through radio metric Doppler and range data, (3) real-time orbit and target updates, and (4) "one step" access to trajectory, observable, filter, and mapping information.

These capabilities make it possible to demonstrate the feasibility of removing historical latencies in ground-based radio metric data processing and orbit determination tasks. Several projects have taken advantage of the automated data processing, especially during critical mission scenarios such as maneuvers and aerobraking. In one case of aerobraking operations, which occurred over several months, the need for off-hours staffing for tracking data processing was eliminated. Automated orbit determination has been demonstrated as well; the combination of automated data validation and orbit determination, to be performed in 1999, will enable navigation analysts to monitor more missions simultaneously.

Abbr.: ARDVARC: Automated Radio metric Data Visualisation And Real-time Correction; ARTSN: Automated Real-Time Spacecraft Navigation; DSN: Deep Space Network; JPL: Jet Propulsion Laboratory; MGS: Mars Global Surveyor; MOI: Mars Orbit Insertion; NEAR: Near Earth Asteroid

Rendezvous; TCM: Trajectory Correction Maneuver; RMDC: Radio Metric Data Conditioning, TCP/IP: Transmission Control Protocol - Internet Protocol, TMOD: Telecommunications and Mission Operations Directorate.

1. INTRODUCTION

ARTSN, the Automated Real-Time Spacecraft Navigation system, is the prototype of a data-driven navigation software system for automated spacecraft navigation and monitoring. This prototype is leading to improvements in the efficiency of the navigation analysis process, enabling simultaneous support of additional spacecraft by a single analyst. Additionally, faster orbit solution generation, relative to manual systems, reduces the turn-around time between critical events and the required response, allowing new modes of operation with increased reliability and reduced costs. This is especially important during critical events such as the launch phase, aerobraking, maneuver monitoring, and approach. In this paper, overviews are given of the motivation for this system, its development history, and a component description. The uses of ARTSN components in operations to date are then reviewed, along with samples of results.

2. BACKGROUND

2.1 Motivation

Historically, all interplanetary missions have made use of ground-based radio metric data, such as Doppler and range. Additionally, some missions have made use of optical images or target bodies against a known star field, telmetered to the Earth for processing, to provide target relative position information. With all of these data types, the information is electronically transferred to a ground operations facility where the data is buffered and stored until processed; the latency between observation time and processing time may be from as little as 10 minutes to as long as a few months (depending on the needs of the mission), with 12-24 hours being typical.

Newly received data is merged with already analyzed data and the entire data set is processed via a batch-sequential least squares estimator. In this process, the identification and correction or deletion of invalid data as well as the operation of the software is performed by an analyst operating at a workstation console. The process of fitting the data requires the use of multiple software links and the manual examination of pre-fit residuals to determine which points should be fit and which points should be deleted from the solution. After generating the best estimate of the spacecraft trajectory based on the input models, the analyst must determine the appropriate set of output coordinate frames and mappings that are desired to view the solution and use the software to generate post-fit residuals. Typically this process requires approximately one hour of additional processing time after the data is received by the operations analyst. When it is necessary to evaluate multiple models, as is the normal procedure, multiple analysts must work in parallel or additional processing time is required.

When one considers the complete flow of tracking data from ground stations to the final navigation products, the tasks can be divided into two high-level segments: front-end (i.e. real-time) and back-end (i.e. processing after the fact). The activities of tracking data validation and orbit determination have been performed as back-end functions (see Figure 1); the objective of the ARTSN effort was to demonstrate the feasibility of performing these tasks as front-end activities.

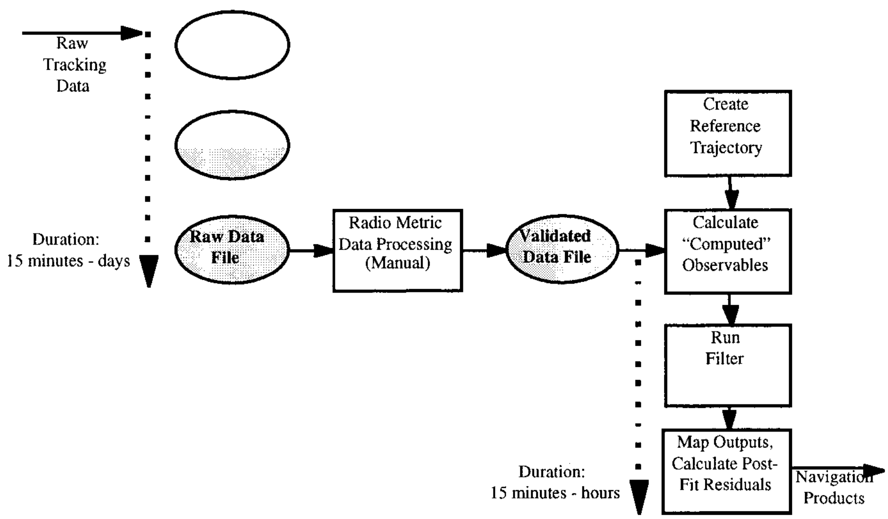

Figure 1. Radio Metric Tracking Data Flow with Current Operational Software

While recent missions have begun to institute greater automation of portions of the orbit determination process, the nature of the automation focuses on the use of scripts and automated routines which use the legacy software instead of the development of a robust system intended for automated use. Although such automated systems have been developed for Earth orbiting missions, they do not have the unique mix of high-fidelity dynamic modeling, measurement modeling, and numerically robust filtering necessary for interplanetary missions. In addition, these systems are not designed for the variety of interplanetary mission scenarios encountered (planetary flyby, aeromaneuvering, libration point orbits, etc.). With such a system, one could automate the generation of predicted spacecraft positions for ground stations, and provide an operational tool for fast turn-around applications. This system is making ground automation of interplanetary navigation tasks more routine, and is serving as a 'stepping stone' to the development of an on-board interplanetary navigation system.

2.2 ARTSN History

The ARTSN development effort was funded by the TMOD Technology Office. The conceptual design of ARTSN was begun in 1994 (Masters, et al., 1994). The ARTSN prototype was completed and tested in mid-1997 (Cangahuala, et al., 1998). Automated orbit determination with ARTSN was first demonstrated in late June 1997; based on the success of these demonstration, a new effort was initiated by TMOD in late 1997 to create a 'next generation' navigation software set, which will be closely allied to the architecture from the ARTSN effort. In addition, the automated data correction module has evolved beyond the prototype stage, and was delivered to flight projects in the summer of 1998.

2.3 ARTSN Description

The current ARTSN prototype has four major components: a data pre-processor, a shell interface, an engine, and data displays. ARTSN validates and corrects observables received via a network connections or file; the receipt of these observables triggers (1) the integration of spacecraft state vectors and dynamic partial derivatives needed to (2) calculate the computed observable and partial derivatives of the observable with respect to relevant parameters. ARTSN then computes (3) estimates of parameters along with their uncertainties and (4) mappings of the spacecraft states and uncertainties to their epochs.

For more information about the ARTSN components, please refer to (Cangahuala, et al., 1998).

3. OPERATIONS RESULTS

There have been several opportunities to work with flight operations teams to demonstrate the capabilities of ARTSN. These collaborations have been valuable, as it significantly reduced the effort needed to gather all the relevant modeling inputs, and the navigation analysts on each missions have provided valuable feedback. Since no single particular mission captures all of the challenges presented to navigation analysts, it has been important to interact with different projects whenever possible.

3.1 Automated Data Validation

It has been possible to deliver the ARTSN data validation code (ARDVARC) separately to navigation teams for various missions. The most specialized input that is requires is a spacecraft trajectory file, which navigation teams must already generate as part of their routine activities. As a result, ARDVARC has made the transition to operational software for several missions. The new operations paradigm is shown in Figure 2.

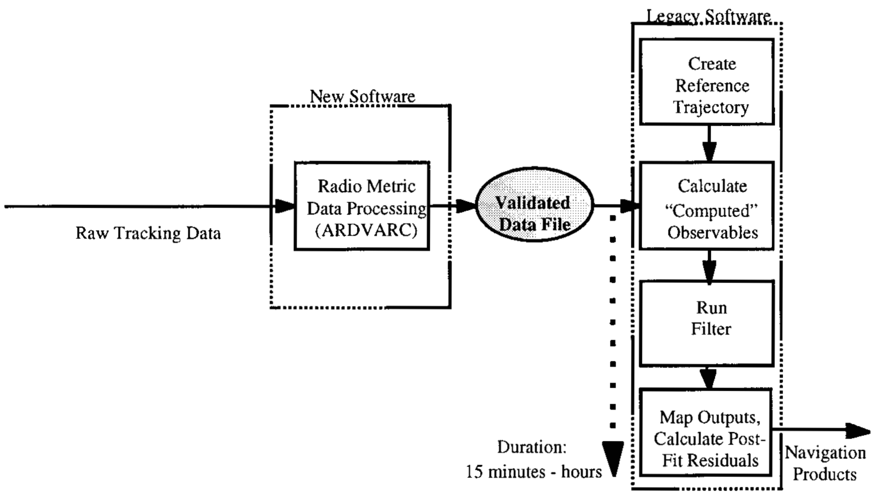

Figure 2. Navigation Operations with Automated Data Validation

3.1.1 Mars Global Surveyor

In the fall of 1998, the resumption of MGS aerobraking at Mars required the rapid turn-around of navigation solutions as the mapping orbital period was reduced. ARDVARC's ability to correct and create tracking data files (for use with the current orbit determination software) in real-time has significantly reduced the latency between the time the data is received and the time the analyst could incorporate it. The need for off-hours staffing for tracking data processing was eliminated.

3.1.2 Near Earth Asteroid Rendezvous (NEAR)

In January 1998 the ARDVARC real-time display was used to observe a maneuver performed by the NEAR spacecraft. Output from the ARDVARC graphic display was used by the NEAR navigation team at JPL to notify the project that the maneuver had been executed. Several parameters were changed in real-time to provide the analysts with the most information; this ability to change the processing configuration in real-time has proven invaluable. A month later, there was an opportunity to observe six thruster firings by the NEAR spacecraft. An annotated plot showing the results of this monitoring, along with the line-of-sight ΔV assessments, was prepared seconds after the end of the data arc.

3.2 AutomatedOrbitDetermination

The opportunities to demonstrate automated orbit determination are more limited than those involving data validation, as there is an initial investment of time needed to prepare the model inputs for each spacecraft. As navigation teams become accustomed to automated data validation, it is anticipated that analysts will attempt to add automated orbit determination (see Figure 3). Not all navigation products required for operations are available at present; however, sufficient post-processing information is available to be of use to the analyst, such as post-fit residuals, parameter estimates, and updated target estimates.

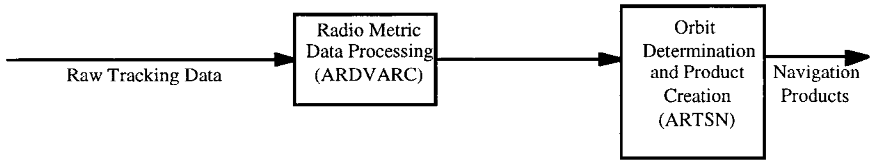

Figure 2. Navigation Operations with Automated Data Validation and Orbit Determination

3.2.1 Mars Pathfinde r

ARTSN's first 'real world' orbit determination test was performed with Mars Pathfinder tracking data. The objective was to produce current state and epoch state solutions over a 76 data arc. These solutions were then used to make encounter estimates; in both modes the ARTSN estimate agreed with that generated by the Pathfinder navigation team to within less than half of the Pathfinder estimate uncertainty, which is suitable for station predict generation and maneuver design. Table 1 shows the comparison of B-plane estimates for a set of ARTSN current state solutions to the solution prepared by the Mars Pathfinder navigation team.

Table 1. Comparison of ARTSN Current-State Mapped B-Plane[1] Estimates vs. Solution Prepared by Mars Pathfinder Navigation Team

	Mars Pathfinder Navigation Team Solution (Doppler / Range)	ARTSN (Doppler/Range)	ARTSN (Doppler Only)	ARTSN (Range Only)
B•R (km)	-1797.62	-1795.3	-1805.3	-1767.6
B•T (km)	-4505.82	-4504.1	-4498.4	-4515.3

A demonstration was also performed using an unedited recording of a DSN broadcast of the final two weeks of Mars Pathfinder before entry into the Martian atmosphere. This time span included the final trajectory correction maneuver, TCM-4.

[1] Planetary targeting is usually expressed in terms of the B-plane, a plane passing through the center of a target body and perpendicular to the incoming approach hyperbola asymptote of the spacecraft. "B•T" is the intersection of the B-plane with the ecliptic and "B•R" is a 'southward' pointing vector in the B-plane that is perpendicular to B•T and making a right handed system R, S, T, where S is the incoming asymptote.

4. CONCLUSIONS

The original objective of this effort has been met; ARTSN components have been used successfully to perform deep space navigation tasks in an automated fashion for the first time. The current mission operations paradigm has now changed with this introduction of this autonomous data processing capability.

Now that prototypes of automated navigation software exist, the next steps to streamlining the navigation process are to (i) automate the incorporation of information from spacecraft telemetry (thruster firings, attitude changes, etc.) into the automated filter, and (ii) design and demonstrate a regulator which can use updated trajectory estimates to create products such as pointing predicts TCM designs.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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